DEFENSE TECHNICAL INFORMATION CENTER

Information for the Defense Community

DTIC® has determined on 5/29/13 that this Technical Document has the Distribution Statement checked below. The current distribution for this document can be found in the DTIC® Technical Report Database.

☒ **DISTRIBUTION STATEMENT A.** Approved for public release; distribution is unlimited.

☐ **© COPYRIGHTED.** U.S. Government or Federal Rights License. All other rights and uses except those permitted by copyright law are reserved by the copyright owner.

☐ **DISTRIBUTION STATEMENT B.** Distribution authorized to U.S. Government agencies only (fill in reason) (date of determination). Other requests for this document shall be referred to (insert controlling DoD office).

☐ **DISTRIBUTION STATEMENT C.** Distribution authorized to U.S. Government Agencies and their contractors (fill in reason) (date determination). Other requests for this document shall be referred to (insert controlling DoD office).

☐ **DISTRIBUTION STATEMENT D.** Distribution authorized to the Department of Defense and U.S. DoD contractors only (fill in reason) (date of determination). Other requests shall be referred to (insert controlling DoD office).

☐ **DISTRIBUTION STATEMENT E.** Distribution authorized to DoD Components only (fill in reason) (date of determination). Other requests shall be referred to (insert controlling DoD office).

☐ **DISTRIBUTION STATEMENT F.** Further dissemination only as directed by (insert controlling DoD office) (date of determination) or higher DoD authority.

Distribution Statement F is also used when a document does not contain a distribution statement and no distribution statement can be determined.

☐ **DISTRIBUTION STATEMENT X.** Distribution authorized to U.S. Government Agencies and private individuals or enterprises eligible to obtain export-controlled technical data in accordance with DoDD 5230.25; (date of determination). DoD Controlling Office is (insert controlling DoD office).

FINAL TECHNICAL REPORT

'Microstructural Design for Stress Wave Energy Management'

ONR Grant No: N00014-09-1-0547
Period of Performance: March 1, 2009 – September 30, 2012
ONR Program Officer: Dr. Roshdy G. Barsoum

PI: Sia Nemat-Nasser
Co-PI: Alireza Vakil-Amirkhizi

University of California, San Diego
Jacobs School of Engineering
Center of Excellence for Advanced Materials
9500 Gilman Drive, La Jolla, CA 92093-0416
Phone (858) 534-4914
Fax (858) 534-2727
Email: sia@ucsd.edu

Submitted April 2013

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
15-04-2013	Final Technical Report	March 1, 2009 - September 30, 2012

4. TITLE AND SUBTITLE	
'Microstructural Design for Stress Wave Energy Management'	5a. CONTRACT NUMBER
	5b. GRANT NUMBER N00014-09-1-0547
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Dr. Siavouche (Sia) Nemat-Nasser (PI) UCSD Center of Excellence for Advanced Materials Department of Mechanical and Aerospace Engineering	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
The Regents of UC San Diego UCSD Office of Contract and Grant Administration 9500 Gilman Drive, La Jolla, CA 92093-0934	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
Office of Naval Research ONR 331 875 North Randolph Street Arlington, VA 22203-1995	ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The objective of this research program is controlling wave propagation in solids by meticulous design of the microstructure. We have established the concept of managing the essential characteristics of propagating stress waves including the wave travel direction (phase planes and energy flux), stress tensor polarization, amplitude and attenuation, and inherent mode of energy (pressure or shear). The approach to achieve such control is to design the heterogeneous microstructure of at the medium at microscopic level, thereby producing highly anisotropic and essentially homogenous elastic properties at the wavelength of interest, which are much larger than microstructural length scale. We have implemented the smooth change of elastic anisotropy to guide stress waves within a material, which was verified experimentally by judicious fabrication of a glass fiber reinforced composite. Furthermore, the abrupt change of elastic anisotropy creates an interface that enables us to control the wave scattering (transmission and reflection) as well as the mode of stress-wave energy (pressure and shear). Specifically, a significant portion of the energy of impinging pressure waves can be transferred into shear waves. Then, we have integrated these methods with conventional mechanisms for shear dissipation (i.e. viscoelasticity) to control the amplitude, energy, and direction of propagating stress-waves in a multilayered structure.

15. SUBJECT TERMS

Stress waves, energy management, anisotropy, wave redirection, scattering, multilayered structure, dissipation, uni-directional fiber reinforced composite

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE		15	Dr. Roshdy G. Barsoum
					19b. TELEPHONE NUMBER *(Include area code)* 703-696-4306 barsour@onr.navy.mil

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

I. AWARD INFORMATION

ONR Award Number	N00014-09-1-0547
Research Title	Microstructural Design for Stress Wave Energy Management
Principal Investigator	Siavouche (Sia) Nemat-Nasser
Organization	UC San Diego, Center of Excellence for Advanced Materials

II. TECHNICAL SECTION

Table of Contents

TECHNICAL OBJECTIVES AND APPROACH

The objective of this research program is controlling wave propagation in solids by meticulous design of the microstructure. We have established the concept of managing the essential characteristics of propagating stress waves including the wave travel direction (phase planes and energy flux), stress tensor polarization, amplitude and attenuation, and inherent mode of energy (pressure or shear). The approach to achieve such control is to design the heterogeneous microstructure of at the medium at microscopic level, thereby producing highly anisotropic and essentially homogenous elastic properties at the wavelength of interest, which are much larger than microstructural length scale. We have implemented the smooth change of elastic anisotropy to guide stress waves within a material, which was verified experimentally by judicious fabrication of a glass fiber reinforced composite. Furthermore, the abrupt change of elastic anisotropy creates an interface that enables us to control the wave scattering (transmission and reflection) as well as the mode of stress-wave energy (pressure and shear). Specifically, a significant portion of the energy of impinging pressure waves can be transferred into shear waves. Then, we have integrated these methods with conventional mechanisms for shear dissipation (i.e. viscoelasticity) to control the amplitude, energy, and direction of propagating stress-waves in a multilayered structure.

SUMMARY OF ACHIEVEMENTS

The proposed methods for managing stress-wave energy are summarized and verified in the following sections:

1) Redirecting stress waves in solids

a. Continuous wave redirection using spatially variable elastic anisotropy

We have controlled stress-wave propagation in solids through imposing a gradual change of anisotropy in the material elasticity tensor. In this section, we have incorporated a transversely isotropic material with a smoothly varying axis of anisotropy. We have showed that if this axis initially coincides with the stress-wave vector, then the energy of the plane pressure waves would closely follow this gradually changing preferred direction. We have used a glass fiber-reinforced composite to induce the required anisotropy, and to experimentally demonstrate the management of stress-wave energy in a desired trajectory (Figure 1-3, courtesy of Amirkhizi et al. Wave Motion, 2010). The material has isotropic mass-density and is considered homogeneous at the scale of the considered wavelengths (λ=1.5-3 mm, f=1 MHz), even though microscopically it is highly heterogeneous (microstructure length scale: 100 μm).

We have used a special layup of uniaxial glass fiber reinforced composite to induce the designed anisotropy and its smooth trajectory, which is essentially transversely isotropic with a preferred axis x_3. In baseline model A, x_3-axis is parallel to the X-direction at each point within the sample, while in the other sample, model B, the direction of the x_3-axis follows a smoothly curving path around the central cavity. Figures 1-3 show that the designed gradual change of anisotropy splits and redirects stress waves around a target object and then re-combine them on the opposite side of the object (referred to as one dimensional "acoustic cloaking" in the literature).

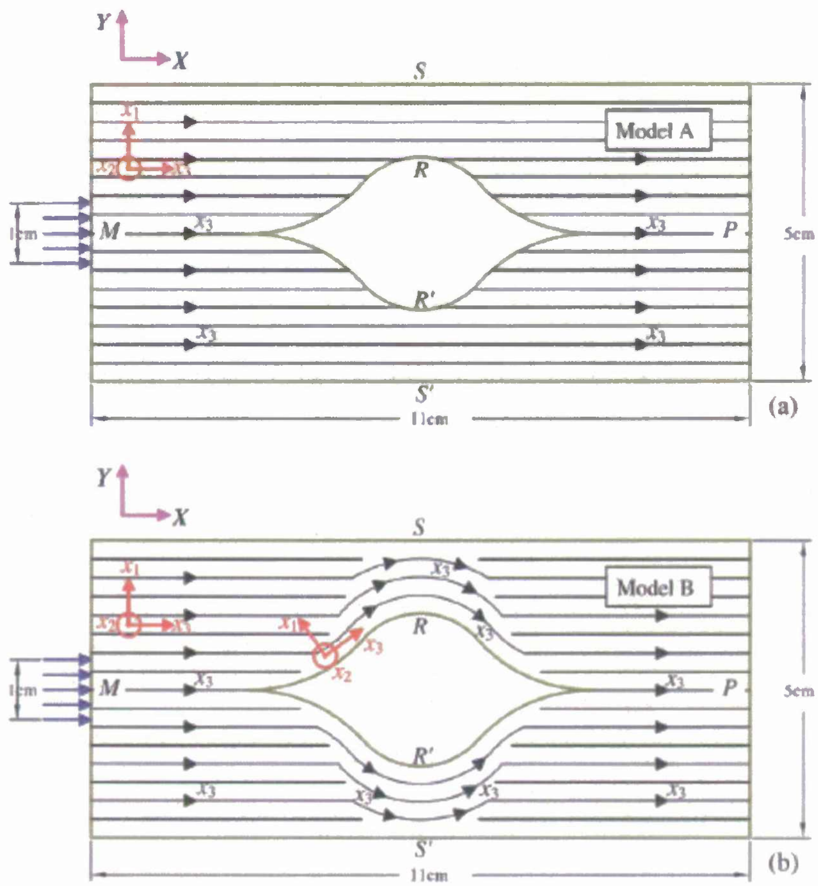

Figure 1: Orientation of the elastic anisotropy axis, the x_3-axis, in: (a) the baseline model with uniformly straight anisotropy axis, and (b) with an anisotropy axis that follow the indicated curved path around the central cavity.

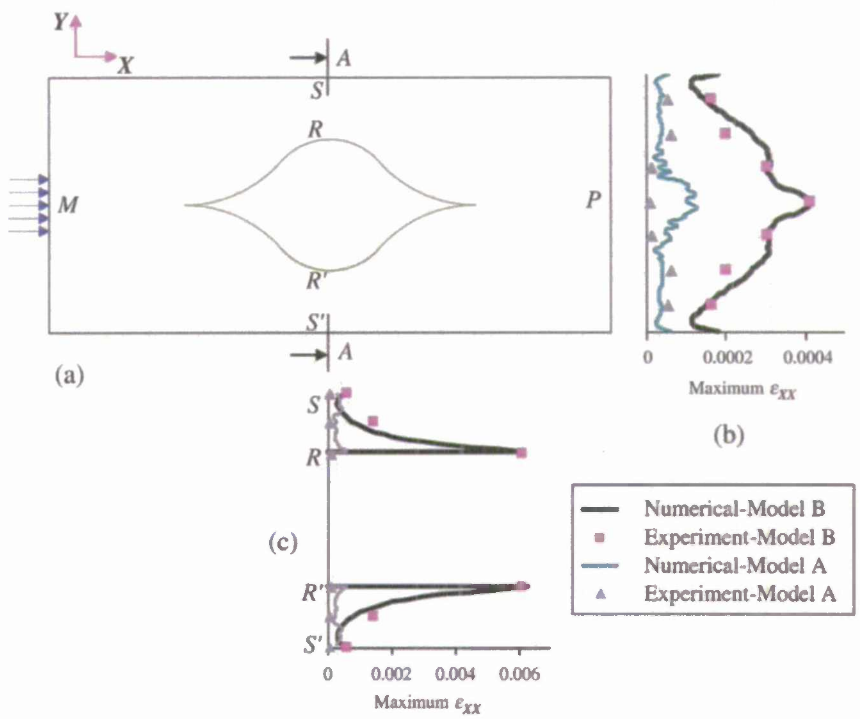

Figure 2: (a) Geometry of the model, (b, c) Numerical results in central excitation and comparison with experimental data. The light and heavy solid lines are the maximum amplitude of the axial strain as calculated in numerical simulation for models A (baseline with constant anisotropy) and B (axis of highest stiffness follows a smoothly curving path around the central cavity). The solid squares and triangles are experimentally measured voltage signals by ultrasonic transducers. In (b) the numerical simulation results and experimental data are taken at the end surface of the sample, while (c) shows these quantities at cross section A–A. In each of the two graphs, only the peak experimental and numerical values for sample B are normalized to have the same geometric magnitude. The normalization factors for graphs (b) and (c) are different. The experimental and numerical profiles for model B are in close agreement, but they are substantially different than those in model A.

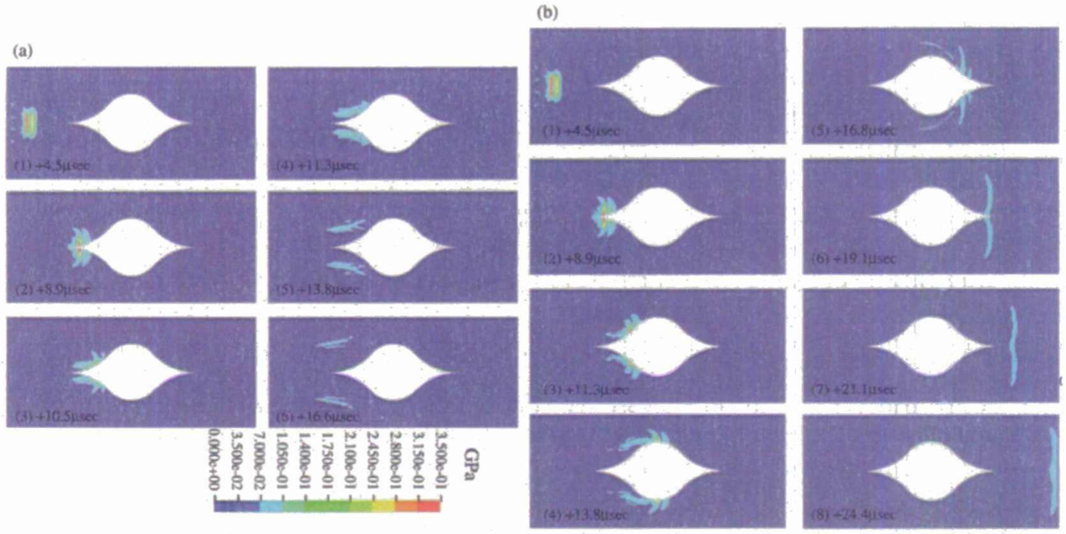

Figure 3: (a) The von Mises stress contours from numerical simulation of model A, plotted for a selected time sequence. As the plane wave encounters the stress-free surface of the central cavity, it is reflected off that surface, scattering throughout the model. (b) The von Mises stress contours from numerical simulation of model B, plotted for a selected time sequence. It shows how each of the two wave packets has traveled, one above and the other below the central cavity, finally join to form a single packet of the plane wave that then travels along the x_3- or wave vector direction, with most of the energy being concentrated at its center.

b. Finite rotation of wave vector at the interface of anisotropic media

We have managed stress wave propagation in solids at the interface of highly anisotropic materials. In strongly anisotropic media, the maximum stiffness direction is the preferred direction for the group velocity and wave-energy flow, particularly in longitudinal and quasi-longitudinal modes. Layered media designed with the proper anisotropic orientations can control the reflected and transmitted longitudinal and/or shear waves. We have developed a program to examine the directions and amplitudes of reflected and transmitted plane waves with various modes of vibration. We have established that the direction of energy travel in the solids can be controlled by designing the orientation of anisotropy of interfacing media, while the local elastic moduli of both materials are kept constant (Figure 4). Using our computer program, even with the same anisotropic material cut at various orientations, we have designed multi-layer plates that redirect and trap energy of traveling wave. See below for further discussion of such designs.

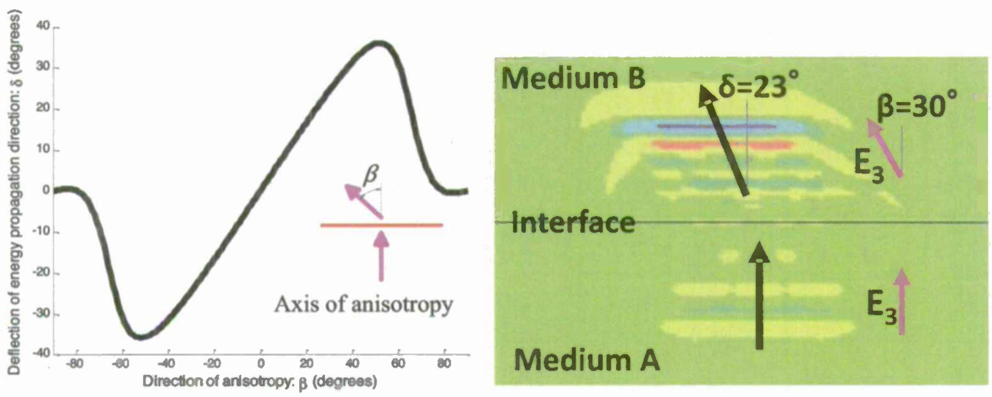

Figure 4: Two semi-infinite elastic media (A and B) are considered with rigid bonding at the interface. Each media is transversely isotropic where the orientation of axis of anisotropy is shown (Medium A: normal to the interface plane; Medium B: deviating an angle β with respect to the anisotropy of medium A). This figure shows the variation of the deflection angle of the energy of transmitted quasi-longitudinal waves (δ) as a function of anisotropy orientation of the medium B (β). We have developed a MATLAB program to calculate the deflection angle based on the slowness surfaces of interfacing materials, which gives an exact solution (left figure). We have verified the results using FEM model for various cases, from which a representative case is shown here (β=30°, δ=23°). The exact solution and FEM model are in very good agreement. It is concluded that the energy of stress-waves can be easily redirected at the interface of anisotropic materials.

2) Changing the mode of stress-wave energy (Pressure to shear) via layering of anisotropic media

The energy content of stress-waves can be transferred from pressure into shear at the interface of anisotropic materials. In section 1b, we showed how the direction of propagation of pressure wave energy can be rotated at the interface of strongly anisotropic materials. In this section, we exploit wave scattering at the interface of anisotropic materials in order to transfer a significant portion of pressure wave energy into shear wave energy. This transfer is extremely beneficial since shear wave energy can be dissipated using viscoelastic mechanism.

Figure 5 shows an example of wave scattering at the interface of identical transversely isotropic materials except for the specified orientation of local material axes. It is noted that a smart design results in transferring almost half of pressure wave energy into shear wave energy.

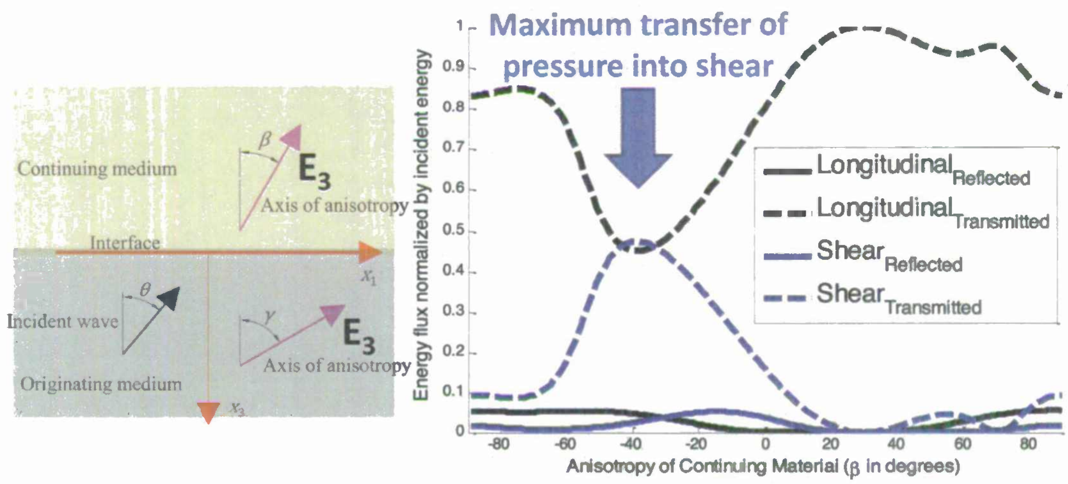

Figure 5: An incident quasi-longitudinal wave with its energy mostly in the pressure mode is propagating with an angle of θ = 15° with respect to the interface of two transversely isotropic materials with highest axis of anisotropy of γ = 30° and variable β. The energy fluxes of scattered wave (transmitted and reflected) in pressure and shear mode are plotted as functions of anisotropy orientation (β) of a semi-infinite medium. It is observed that significant amount of energy of the impinging wave is transferred into shear mode. The elastic moduli correspond to a glass fiber reinforced plastic sample.

3) Development of dissipative materials: Polyurea based foam

The motivation for synthesizing Polyurea based foam consists of several factors including high energy absorption, light weight, higher elastic modulus to density ratio (compared with Polyurea), and collapsible voids under extreme loading. Pure Polyurea offers unique properties such as increased shear stiffness under large pressure, which is beneficial in controlling elastic stress-waves and shock waves. A porous structure with Polyurea matrix can be integrated into a layered structure to enhance management of stress-waves.

Figure 6 shows the porous microstructure of Polyurea-based foam with void sizes ranging 100-250μm. We characterized the synthesized samples for mechanical and chemical properties: we measured storage and loss moduli using DMA at various temperatures (Figure 7); we studied stress-strain behavior and relaxation pattern under uniaxial compression (Figure 8); we measured pressure wave speed using ultrasonic transducers; we also performed IR spectroscopy to identify the chemicals present in the samples.

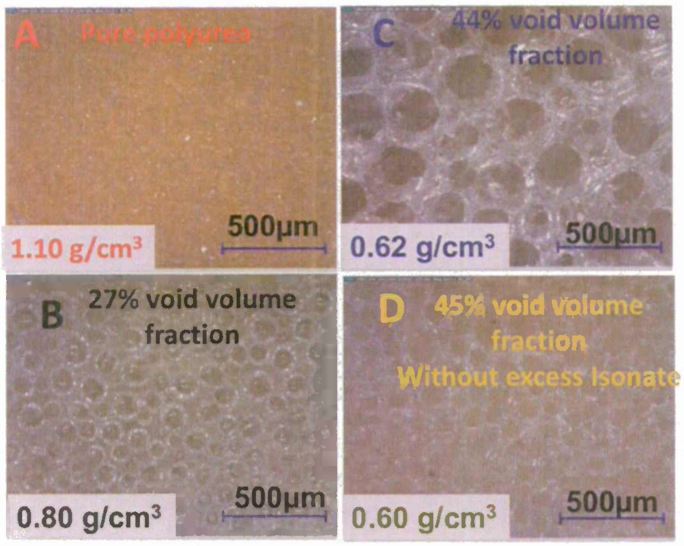

Figure 6: Micrograph of fabricated polyurea and polyurea based foam. The stoichiometry of synthesizing Polyurea is modified to calculate the required weight percentage of Versalink, Isonate, and added water to produce CO_2 bubbles which results in a porous microstructure.

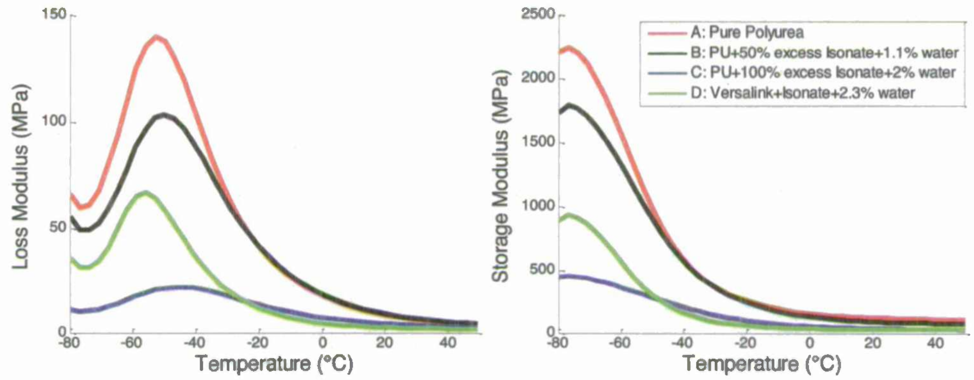

Figure 7: Loss Modulus and Storage modulus versus temperature for samples shown in Figure 6. In porous samples, both moduli are lower than those in pure Polyurea.

We used a micromechanics model to estimate the storage and loss moduli of polyurea with periodically distributed voids, which was then compared to the experimental values (Figure 9). The comparison shows that the modified stoichiometry (due to presence of water that is needed for CO2 production) to synthesize foam samples affect the mechanical properties of the matrix, which is stiffer than pure polyurea.

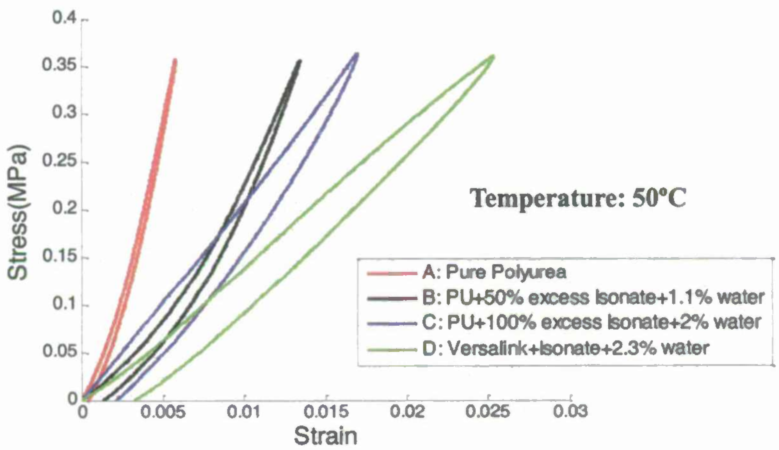

Figure 8: Elastic behavior under uniaxial compression at 50°C.

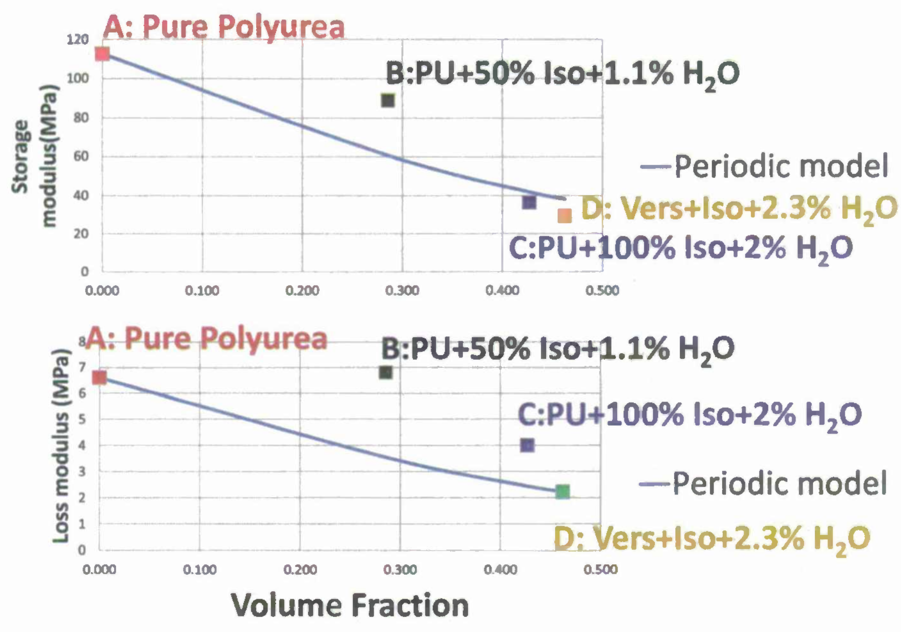

Figure 9: Micromechanics periodic model to estimate moduli of porous materials and comparison with measured value (square dots).

4) Controlling transmission and reflection of pressure and shear waves in a multilayered anisotropic structure

Multilayered structures consisting of strongly anisotropic layers enhance the capability of controlling stress waves by providing multiple interfaces that play key roles in transmission and reflection of pressure and shear waves. There will be various design parameters which can be optimized to manage the impinging stress waves as desired. The configuration of layers may include inclination (as in Figure 10) to add an extra design parameter of great potential, since it provides a deviation angle between the wave vector and the preferred direction of anisotropic layers. We have developed a MATLAB program to efficiently calculate the flux of transmitted and reflect energy in pressure and shear mode based on the anisotropy orientation of layers and wave vector direction.

An example of 3-layered structure is shown in Figure 10a where all of the layers are transversely isotropic with specified axis of isotropy. We studied the effect of anisotropy orientation (α) of layer B to illustrate the proof of concept in managing stress-waves. A sinusoidal pulse of load centering at point R is applied normal to the model to induce a longitudinal wave. We calculated the peak of vibration in normal and transverse displacement transmitted to the opposite face (elements in MN) as well as those reflected to the elements in PQ using finite element analysis. The maximum peaks are plotted versus α in Figure 11 with solid lines. The normal vibration is a measure of pressure component of the stress wave and transverse vibration is a measure of its shear component. We observed that a particular choice of anisotropy orientation (α=50°) minimizes the transmitted and reflected pressure wave while maximizing the shear wave effect.

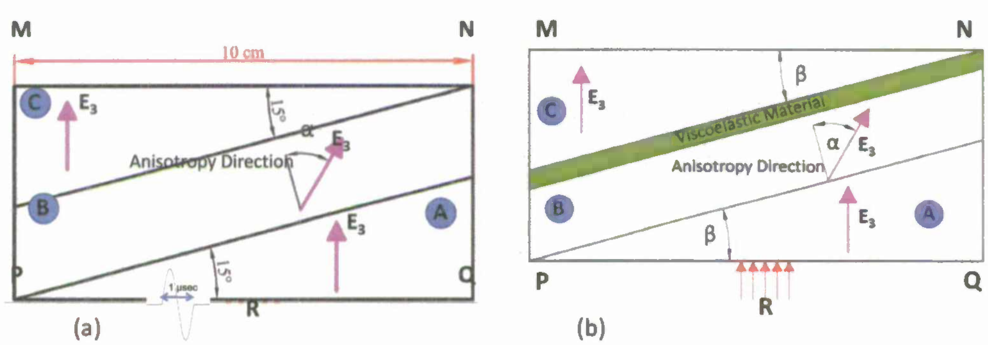

Figure 10: (a) Elastic 3-layered structure composed of transversely isotropic materials with preferred axis E_3, **(b)** integrated multilayered anisotropic structure with a layer of viscoelastic material to dissipate shear wave energy.

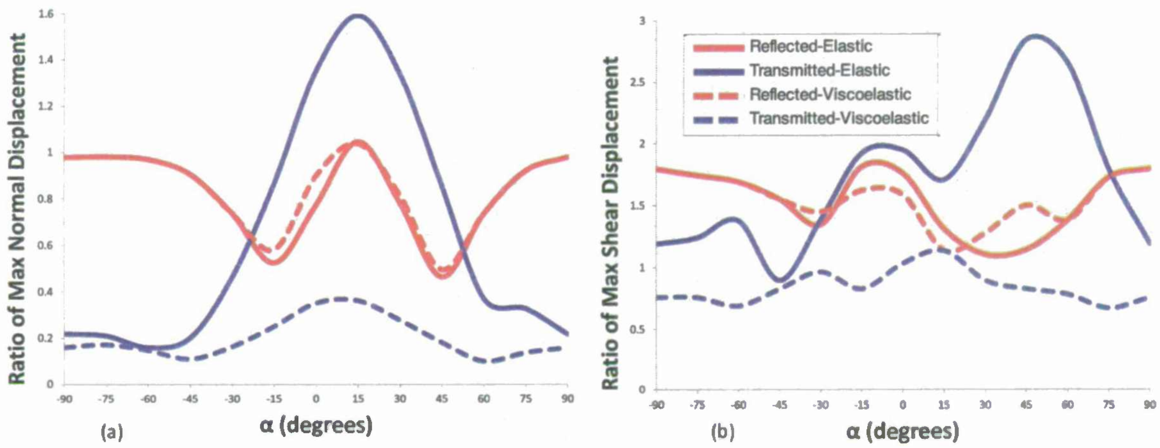

Figure 11: Results of numerical simulation on the elastic model in Figure 10a in solid lines, and dissipative model in Figure 10b in dashed lines. Ratio of maximum (a) normal and (b) shear displacement to that induced by the incident load are plotted versus anisotropy orientation α. The blue lines represent the calculated amplitude of transmitted wave to the opposite face MN, while the red lines represent the calculated amplitude of reflected waves back to the PQ face.

5) Integration of methods for stress-wave energy management

We have demonstrated the integration of various methods of controlling stress-wave propagation in solids with each other: conventional mechanism of viscoelasticity has been used extensively in the literature and practice to dissipate undesirable disturbances; we have developed the constitutive model of Polyurea and experimentally verified to enhance failure mitigation under high pressure shock condition; we fabricated a porous microstructure with Polyurea matrix and characterized (section 3) to further enhance energy dissipation; and finally we controlled transmission and reflection of pressure and shear waves at the interface of anisotropic layers (sections 1b, 2) or in a multilayered configuration (section 4).

We illustrate an example here to show a combination of methods mentioned above. We investigated how pressure wave energy can be transferred into shear wave energy. Now by incorporating a shear dissipative material, we intend to dissipate the shear wave energy in order to manage a potentially damaging incoming pressure wave. Figure 10b shows the configuration used for numerical modeling and the results are expressed using dashed lines in Figure 11. Comparing these results with the elastic case presented in section 4 by solid lines, we observed that while the reflected pressure and shear waves are remained almost the same, the transmitted pressure and shear waves are diminished by a significant factor. Thus, combination of stress-wave management via layering of anisotropic materials and viscoelastic shear dissipation resulted in enormous control on impinging stress-waves.

6) Layered structures consisting of highly anisotropic carbon fiber reinforced composite

Unidirectional fiber reinforced composites are excellent choices to experimentally verify the suggested methods for managing stress-waves, since they provide high anisotropy in elastic moduli. They can be modeled as transversely isotropic materials with a preferred direction, where the wave speed is the highest of all directions. We used glass fiber reinforced polymer in section 1a in order to redirect and guide pressure waves. The elastic modulus is about 3.2 times greater than that of transverse direction, which allows for guiding stress-waves in a smooth curved path. In order to further expand the control on stress-waves, we sought carbon fiber reinforced composites for the enormous anisotropy they offer (E_3/E_1=13).

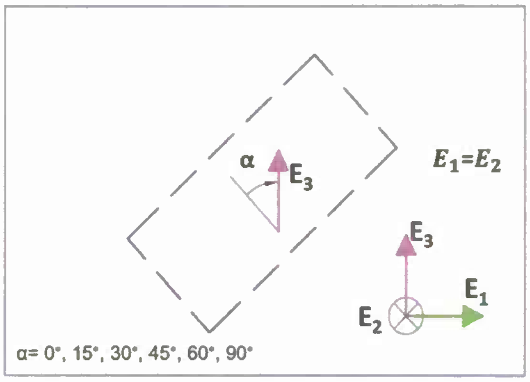

Figure 12: Thin panel of unidirectional carbon fiber reinforced composite with preferred axis x_3. Various samples are cut out of the panel with a specified angle α in order to achieve the required pieces of anisotropic layers to be assembled to a multilayered structure.

Our purpose is to experimentally verify stress-wave management methods discussed in sections 4 and 5, where the numerical simulations are based on elastic moduli of generic CFRP taken from literature. We ordered 8 customized 16"x16"x1/8" panel of unidirectional CFRP from a manufacturer (DragonPlate). Two 1"x1" samples were cut normal to the fibers and two other samples with 45° angle with fiber direction for wave speed measurements.

We plan to use ultrasonic transducers to measure pressure and shear wave speeds in samples taken from CFRP panel in order to find independent elastic moduli of the composite (Figure 12). We plan to modify the numerical simulations using the measured elastic properties to propose the sizes and orientation of anisotropy of layers in a multilayered structure. The proposed design will be fabricated by cutting various layers out of CFRP panel and assembling in a multilayered design. Then we will investigate wave propagation in the layered structure by sending an elastic stress-wave and measuring signals received at the boundaries using piezoelectric transducers. The measurements will be compared with the numerical model to experimentally verify the concept of stress-wave management in layered structures.

III. SCIENTIFIC AND TECHNICAL PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD

Senior Personnel:
Sia Nemat-Nasser (PI) – MAE Faculty and Director, CEAM
Alireza Vakil Amirkhizi (Co-PI) - Asst. Research Scientist

Technical Personnel:
Jon Isaacs – Sr. Development Engineer

Graduate Student Researchers:
Ahsan Samiee, PhD. Degree conferred Fall 2010
Aref Tehranian, Ph.D. Degree to be conferred Summer 2013

Undergraduate Student Researchers:
Jeffrey Irion (2009)

IV. PUBLICATIONS

<u>Archival Journal Publications</u>

Amirkhizi, A.V., A. Tehranian and S. Nemat-Nasser, "Stress-wave Energy Management through Material Anisotropy," *Wave Motion,* Vol. 47 (2010) 519-536. Also acknowledges DARPA AFOSR FA9550-09-1-0709 to UC San Diego.

Samiee, A., A. Amirkhizi and Sia Nemat-Nasser, "Numerical study of the effect of polyurea on the performance of steel plates under blast loads" *Mechanics of Materials (2013).* In-Press. Also acknowledges ONR N00014-09-1-1126 to UC San Diego.

<u>Non-Referred Publications and Thesis</u>

Tehranian, A., A.V. Amirkhizi, J. Irion, J. Isaacs and S. Nemat-Nasser, "Controlling Acoustic-wave Propagation through Material Anisotropy" *Proceedings of Health Monitoring of Structural and Biological Systems 2009, SPIE 16th Annual International Conference on Smart Structures and Materials*, Vol. 7295 (2009) 72950V1-V4. [Conference Proceeding]. Other ONR grant N00014-06-1-0340 was acknowledged in error.

Tehranian, A., A. V. Amirkhizi and S. Nemat-Nasser, "Acoustic wave-energy management in composite materials," *Proceedings of 2009 SEM Annual Conference and Exposition on Experimental and Applied Mechanics*, ISBN: 978-1-935116-03-5 (2009) [2 page Extended Abstract]. Other ONR grant N00014-06-1-0340 was acknowledged in error.

Tehranian, A., A.V. Amirkhizi and S. Nemat-Nasser, "Use of Anisotropy to Guide Acoustic Wave Along

Desired Trajectories" *Proceedings of Health Monitoring of Structurol ond Biologicol Systems 2010, SPIE 17th Annuol Internotionol Conference on Smort Structures and Moteriols*, Vol. 7650 (2010) 76S00B1 - 76500B4. [Conference Proceeding].

Tehranian, A., A. V. Amirkhizi and S. Nemat-Nasser, "Controlling Wave Propagation in Solids Using Spatially Variable Elastic Anlsotropy" *Proceedings of 2010 SEM Annual Conference and Exposition on Experimentol ond Applied Mechanics*, (2010) [3 page Extended Abstract].

Ahsan Samiee, [Ph.D Thesis] "Performance of Steel-Polymer and Ceramic-Polymer Layered Composites and Concrete Under High-Strain-Rate Loading" Fall 2010.

V. CONFERENCE PRESENTATIONS

'Controlling Acoustic-wave Propagation Through Material Anisotropy' A. Tehranian, A. Amirkhizi, J. Irion, J. Isaacs, S. Nemat-Nasser, SPIE 2009 EAPAD Conference, Health Monitoring of Structural and Biological Systems, San Diego CA, March 2009.

'Acoustic Wave-energy Management in Composite Materials,' A. Tehranian, A. Amirkhizi, S. Nemat-Nasser, SEM 2009 Conference and Exposition on Experimental and Applied Mechanics, Albuquerque, NM, May-June, 2009.

'Use of Anisotropy to Guide Acoustic Waves Along Desired Trajectories,' A. Tehranian, A. Amirkhizi and S. Nemat-Nasser, SPIE 2010 EAPAD Conference, Health Monitoring of Structural and Biological Systems, San Diego, March 2010.

'Controlling Wave Propagation in Solids Using Spatially Variable Elastic Anisotropy,' A. Tehranian, A. Amirkhizi and S. Nemat-Nasser, SEM 2010 Annual Conference, Indianapolis, IN, June 2010.

'Stress-wave Propagation with Negative Phase Velocity,' A. Amirkhizi and S. Nemat-Nasser, 16th USNCTAM, State College, PA, June 2010.

'Controlling Wave Propagation in Solids Using Layered Anisotropic Materials,' A., Tehranian, A.V. Amirkhizi, and S. Nemat-Nasser, *Behovior ond Mechonics of Multifunctionol Moteriols and Composites,* SPIE Annual International Conference on Smart Structures/NDE, San Diego, CA, March 2011. POSTER PRESENTATION.

"Acoustic and Elastic Cloaking Using Non-singular Transformation', A. Tehranian and Sia Nemat-Nasser, IMECE 2013, San Diego CA, November 1S-21, 2013.

VI VITAL STATISTICS:

Number of Conferred PhD's: 1
Number of Ph.D. Degrees to be conferred: 1
Number of Conferred Masters Degrees: 0
Number of Graduate Students: 2
Number of Publications and Reports: 7

MEMORANDUM OF TRANSMITTAL

Dr. Roshdy G. Barsoum
OFFICE OF NAVAL RESEARCH
875 North Randolph Street, Arlington, VA 22203-1995

ONR REG SAN DIEGO-N66018
140 Sylvester Road, Bldg 140, Room 218, San Diego, CA 92106-3521

Defense Technical Information Center
8725 John J Kingman Road Ste 0944,Fort Belvoir, VA 22060-6218

Naval Research Laboratory
Attn: Code 5596, 4555 Overlook Avenue, SW, Washington DC 20375-5320

☐ Reprint (Orig + 2 copies)

☐ Technical Report (Orig + 2 copies)

☐ Manuscript (1 copy)

☒ **Final Progress Report (1 copy)**

☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: N00014-09-1-0547

REPORT TITLE: Microstructural Design for Stress Wave Energy Management

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

S. Nemat

Professor Sia Nemat-Nasser (PI)
UC San Diego Jacobs School of Engineering
Center of Excellence for Advanced Materials
La Jolla, CA 92093-0416
Tel: (858) 534-4914
Email: sia@ucsd.edu